Detecting Quantum Light
Part I

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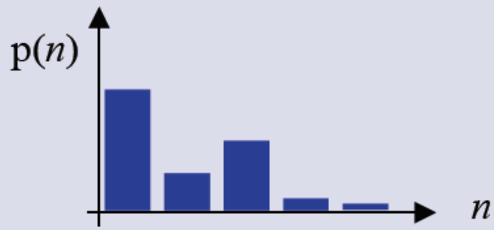
Bad Honnef

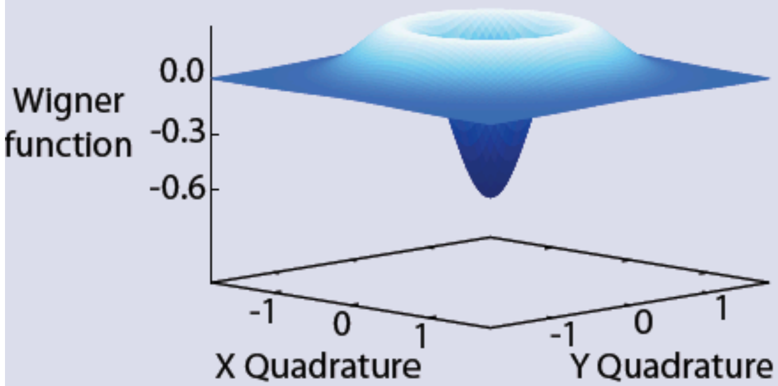
- Quantum states of light: How can we detect them?

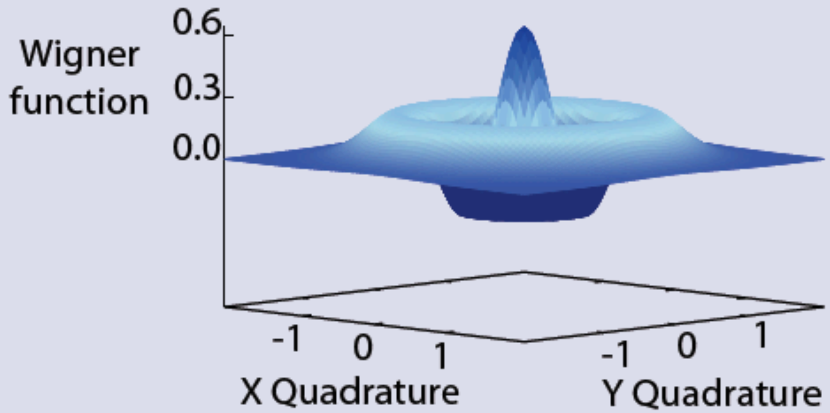
- Photon number resolved detection by TMD

$$|\Psi\rangle = \frac{1}{N}\sum_n c_n \, |n\rangle \,, \quad p(n) = c_n^* c_n = \mathrm{tr}\left[\, |n\rangle \langle n| \, \hat{\rho} \,\right]$$



Wigner functions

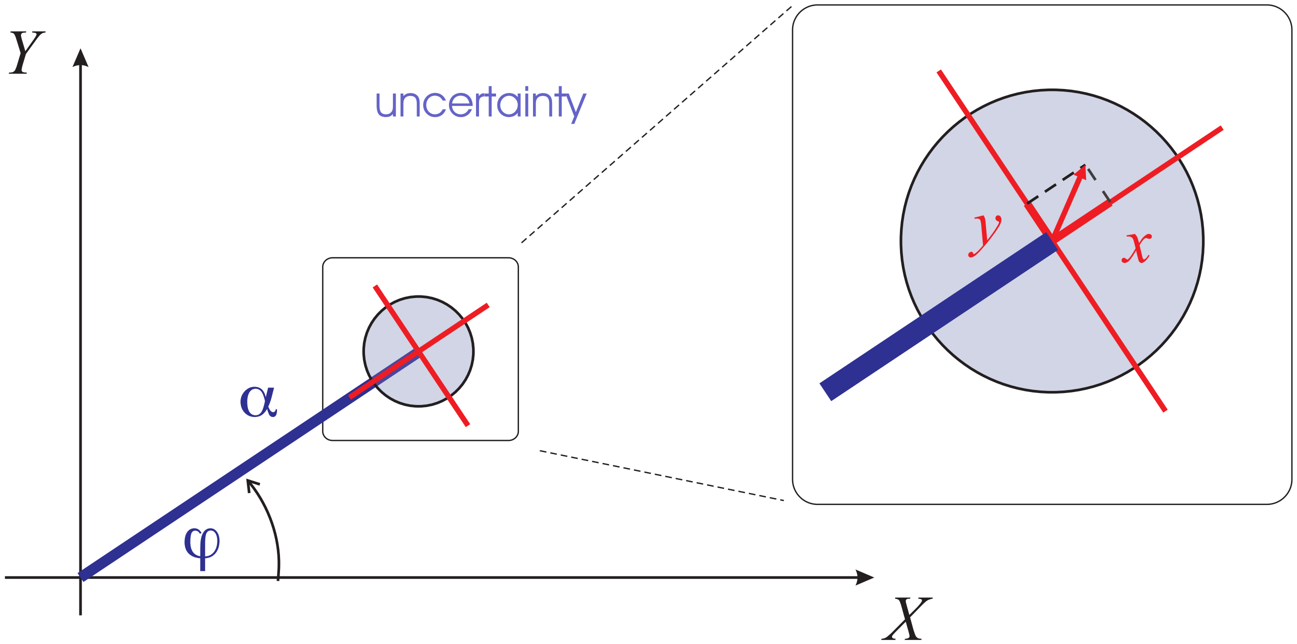




$$W(X,Y) = \frac{1}{2\pi} \int dq \langle X - \frac{1}{2} | \hat{\rho} | X + \frac{1}{2} \rangle e^{iqY}$$

Phase space diagrams: single mode field

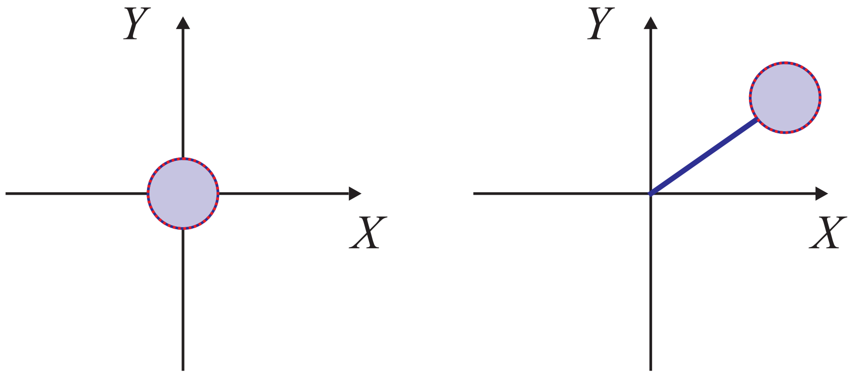
x: amplitude-
y: phase- quadrature



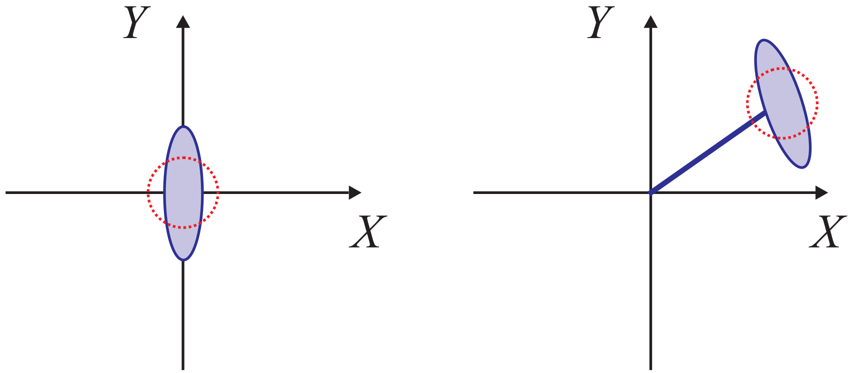
α: complex field
φ: optical phase

CV and squeezed states

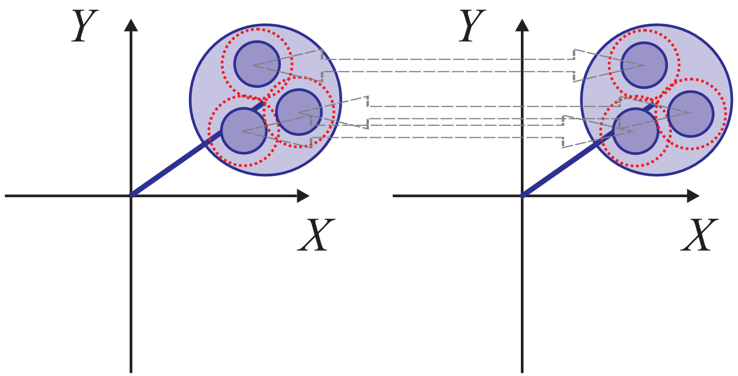
coherent states



squeezed states

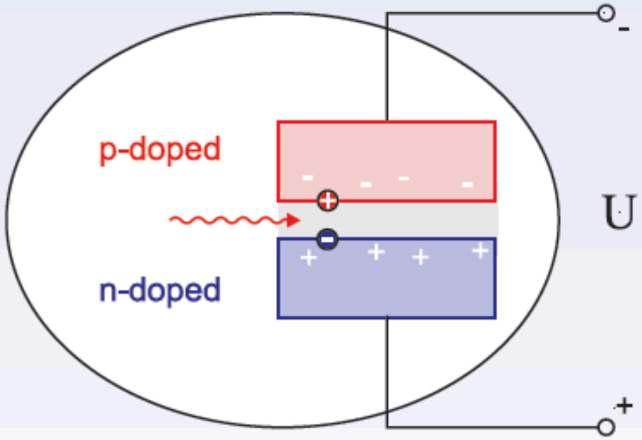


entangled states



Detection of light

Semiconductor photo-diodes

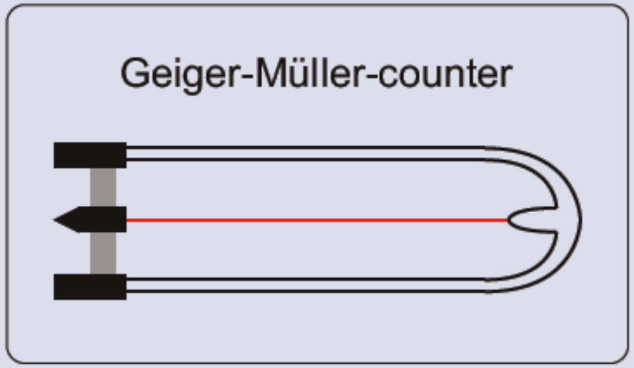


$$i(t) = \frac{n_e(t)e}{\Delta t} = \frac{P_{opt}(t)e}{\hbar\omega\eta_{det}}$$

- high quantum efficiencies possible
- electronic noise masks single photons out:
  no single-photon sensitivity

Detection of single photons?

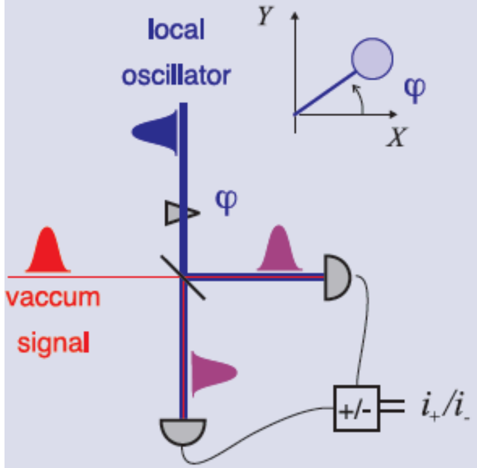
Avalanche photo-diodes (APD)

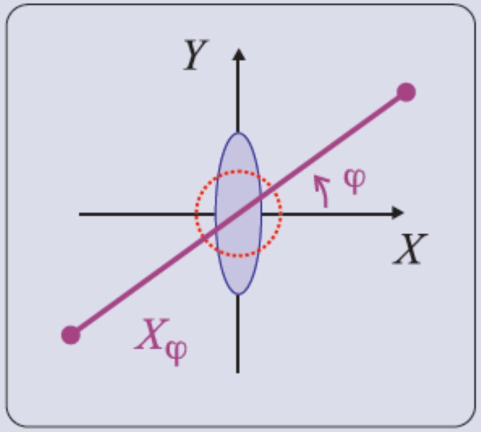


- single photons cause charge carrier-avalanches:
  single-photon sensitivity
- deadtimes limit repetition rates
- loss of information about statistics

Homodyne tomography

Detection scheme





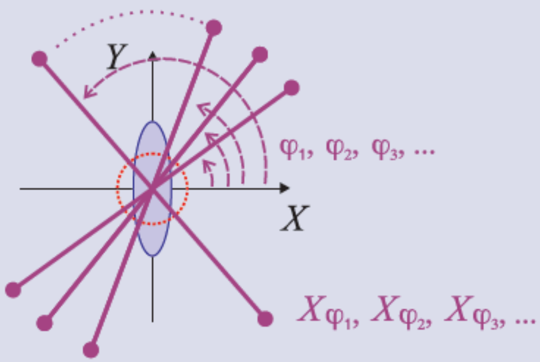
semiconductor photo-diodes

quadrature measurement:

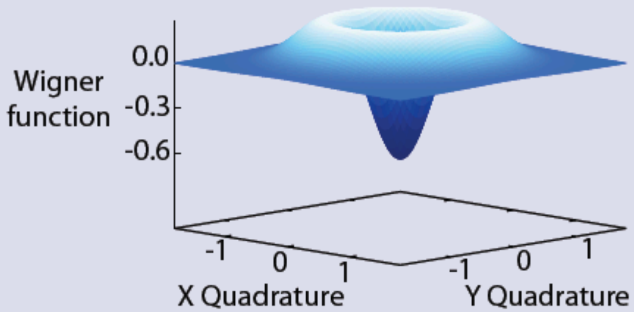
$$\hat{X}_\varphi = \hat{a}e^{-i\varphi} + \hat{a}^\dagger e^{i\varphi}$$

$$\langle \hat{N}_d - \hat{N}_c \rangle \propto \beta^* \, \hat{a} + \beta \, \hat{a}^\dagger =$$

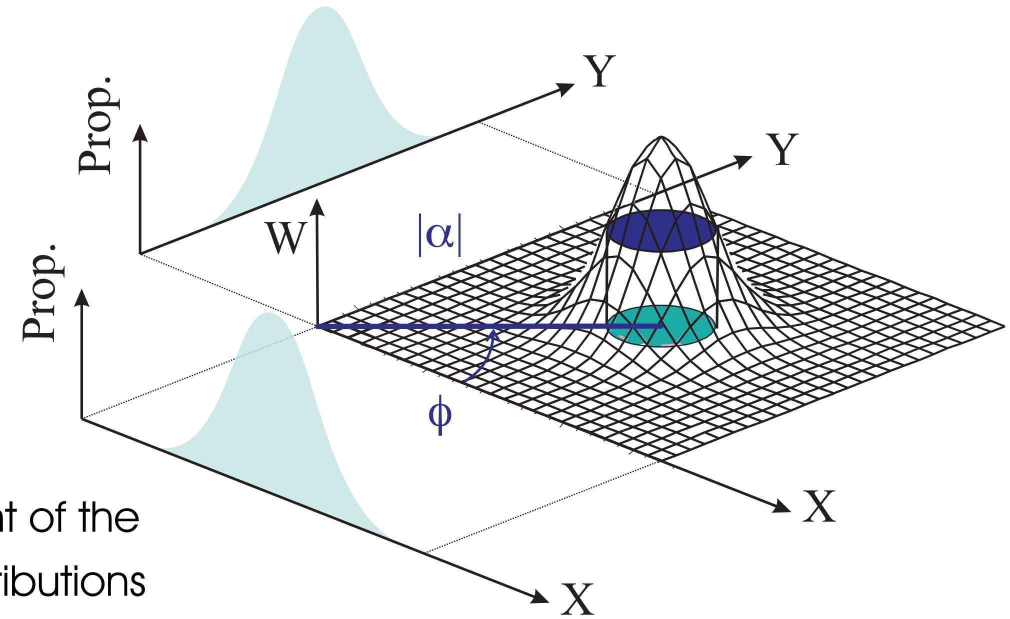
$$|\beta| \, \langle \hat{X}^a_\varphi \rangle$$



$\Rightarrow$



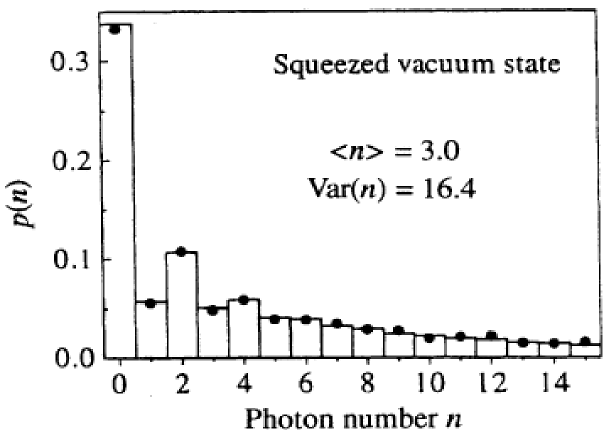
Phase space representation



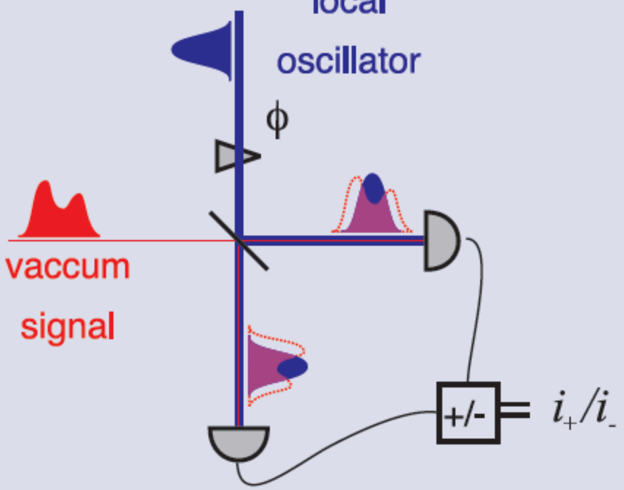
measurement of the
marginal distributions

Reconstruct:
photon number statistics

G. Breitenbach,
S. Schiller & J. Mlynek, Nature
387, (1997)

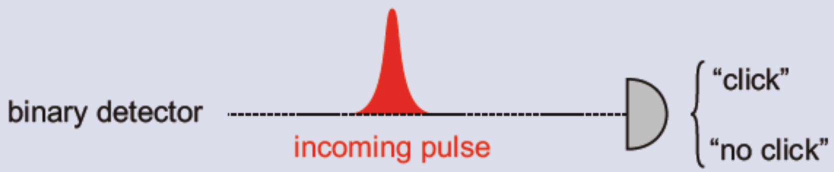


Detection scheme



- quadrature measurement: projection on Gaussian states
- filters on local oscillator mode
  $\hat{A}^{\dagger}_{\xi_i} \equiv \int d\omega \xi_i(\omega)\hat{a}^{\dagger}(\omega)$

Detection with single photons

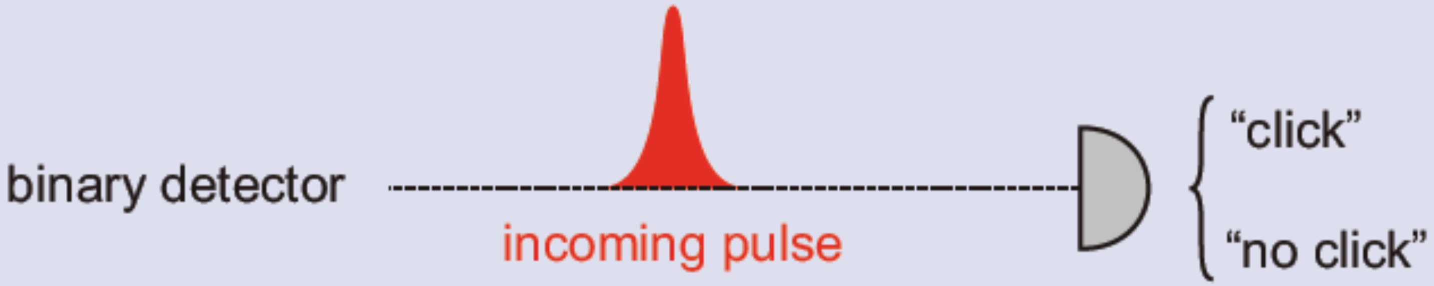


- single-photon sensitivity
- loss of information about statistics
- non-Gaussian operation

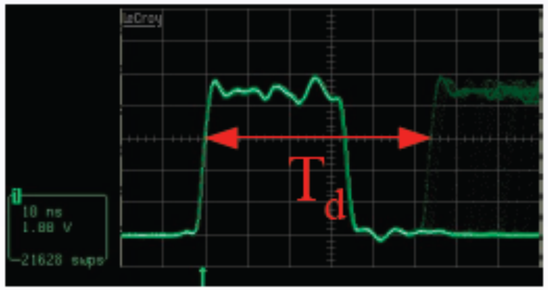
POVM: $\hat{M} = 1 - |0\rangle\langle 0|$

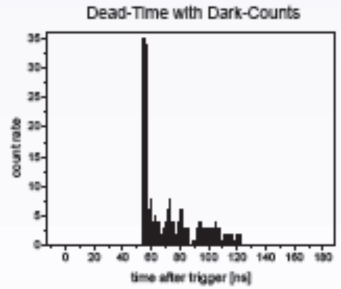
Basic properties of APDs

How much information can be gained with APDs?



- Quantum efficiency $\eta = \frac{\text{detected events}}{\text{incident photons}}$
- Dark count-rate $D =$ detection-events without incident signal
- Deadtimes





Attenuation of light

bright beams: coherent states

intensity

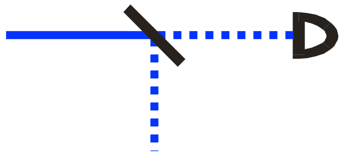
$P \ / \ I$

single photons

detection probability

$I \Rightarrow \eta I$

$\langle \hat{n} \rangle = \eta \langle \hat{n} \rangle$



$P \Rightarrow \eta P$

linear treatment of attenuation

$$|\alpha\rangle = e^{-\frac{1}{2}|\alpha|^2} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle$$

Detection of coherent states

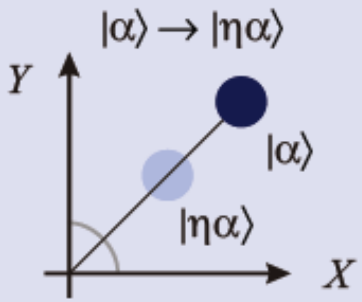
APD-detection: probability for "CLICK":

$$P_{\text{click}} = 1 - p(0) = 1 - e^{-|\alpha|^2}$$

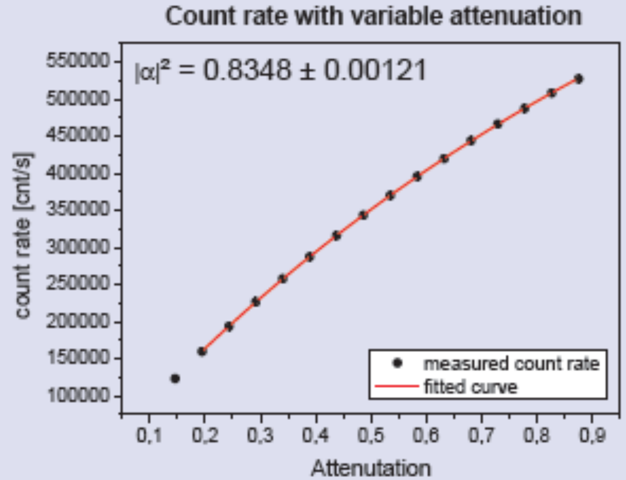
POVM: $\hat{M} = 1 - |0\rangle\langle 0|$

A priori-knowledge: coherent state $|\alpha\rangle = e^{-\frac{1}{2}|\alpha|^2} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle$

Attenuation mesurements with well-calibrated η



$$R = f_{rep}(1-e^{-|\eta|^2|-\alpha'|^2})+D$$



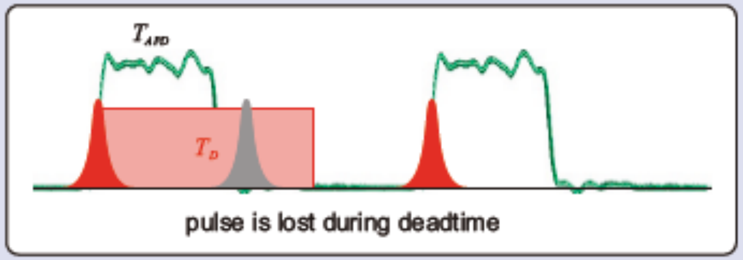
How fast can APDs be operated?

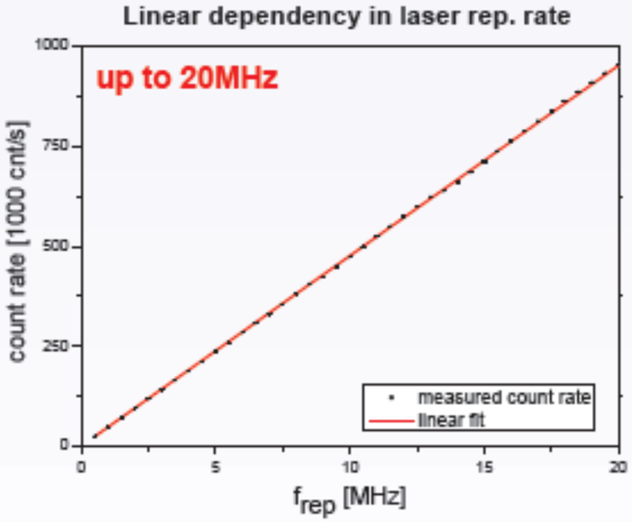
for cw laser light:

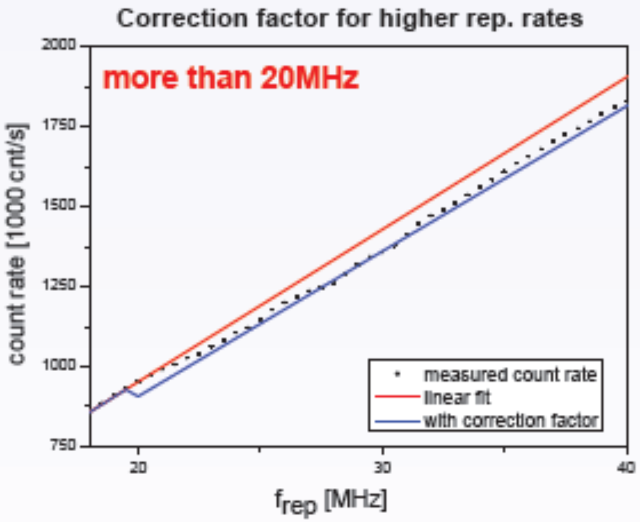
From 1 M counts/s a correction factor must be allowed for

for pulsed laser light

$$R = f_{\text{rep}} \cdot p_{|\Psi\rangle} \cdot p_{\text{APD}} \cdot p_{\text{corr}}$$







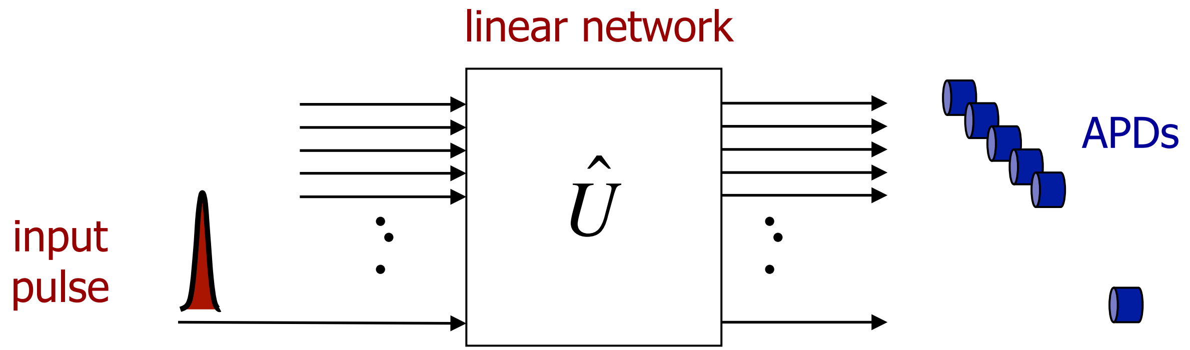
$$R_{\text{C}} = f_{\text{rep}} P_{\gamma} P_{\text{corr}} P_{\text{APD}} = f_{\text{rep}} P_{\gamma}(1 - P_{\gamma}) P_{\text{APD}}$$

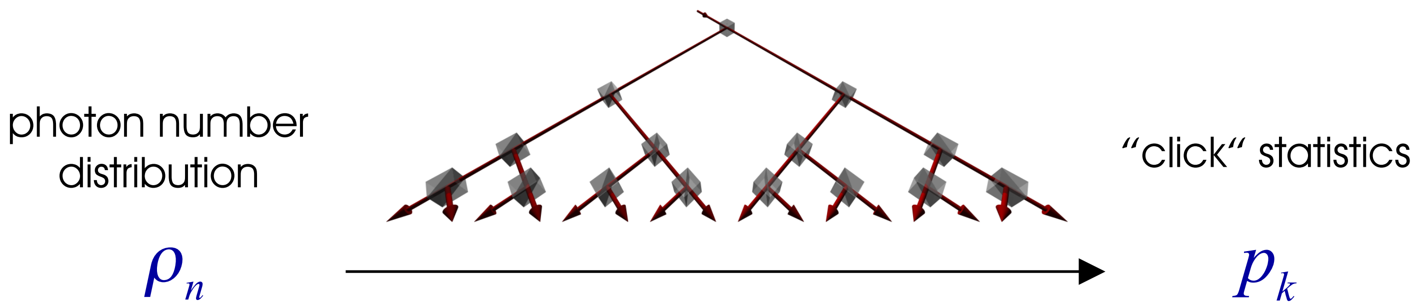
- Quantum states of light: How can we detect them?

- Photon number resolved detection by TMD

Photon number resolution

- Input light in a single mode
- Divide input among many modes
- ensure that there are many more output modes than input photons
- count "clicks" (I.e. presence or absence of photons) in the output modes

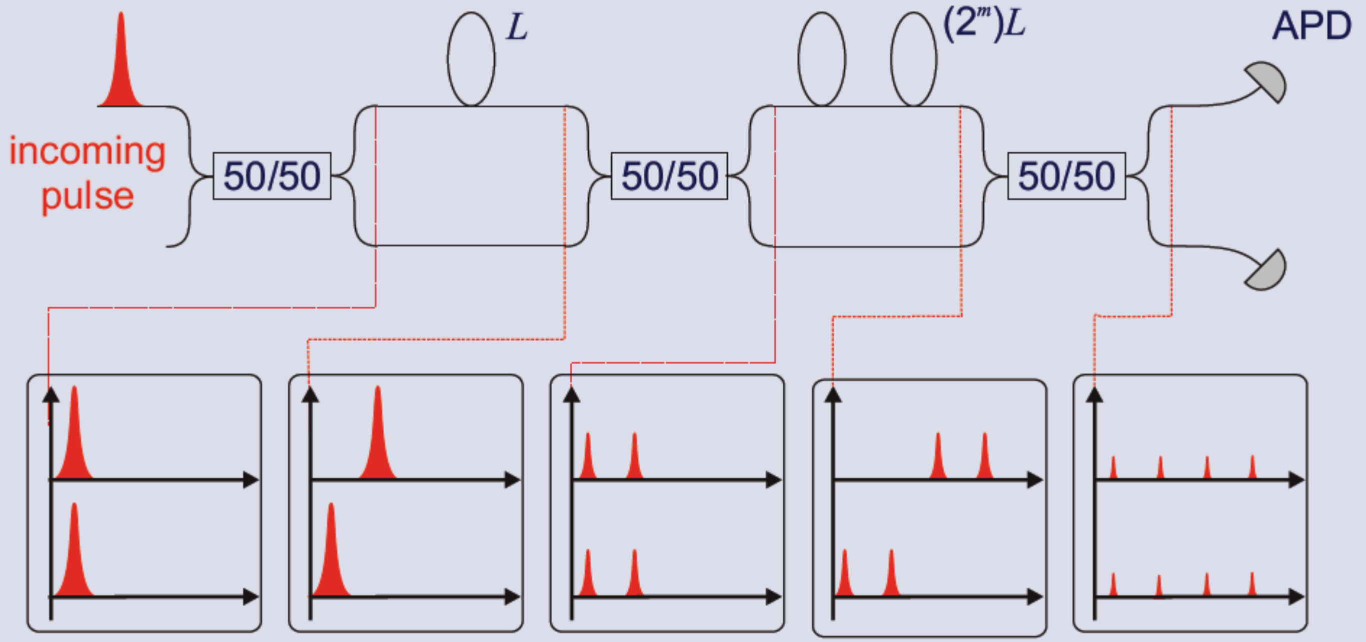




Kok and Braunstein, Phys. Rev. A 63, 033812 (2001).

Time multiplexed detector (TMD)

Distribute photons in temporal modes



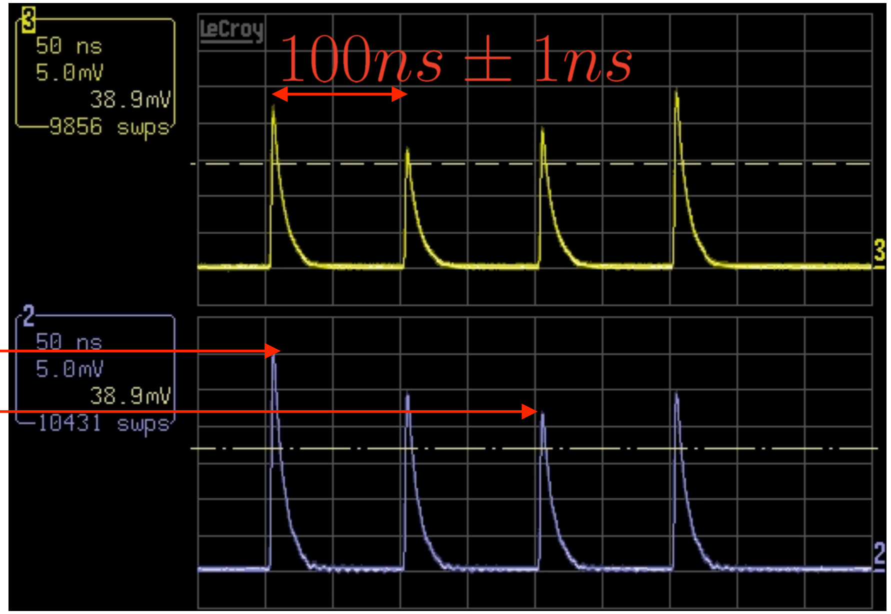
Advantages

- ❖ Off the shelf components
- ❖ Fewer resources that cascade
- ❖ No cryogenics
- ❖ Low dark counts
- ❖ Relatively high efficiency

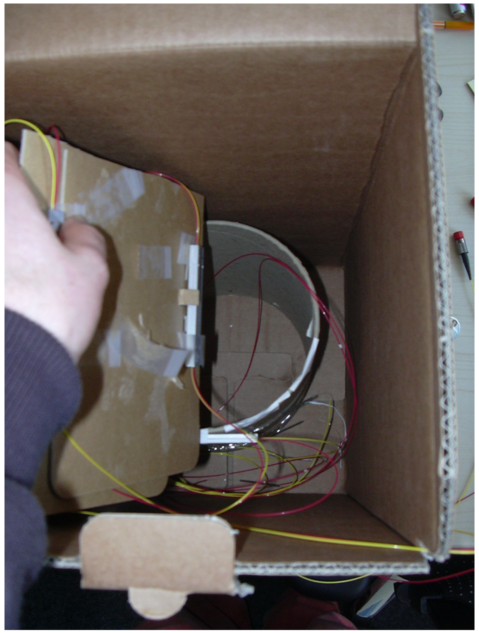
D. Achilles, Ch. S., C. Sliwa, K. Banaszek, I. A. Walmsley, Opt. Lett. 28, 2387 (2003).
D. Achilles, Ch. S., C. Sliwa, et. al., J. Mod. Opt. 51, 1499, (2004).

TMD characteristics

carefully determined
delay lengths (100ns)



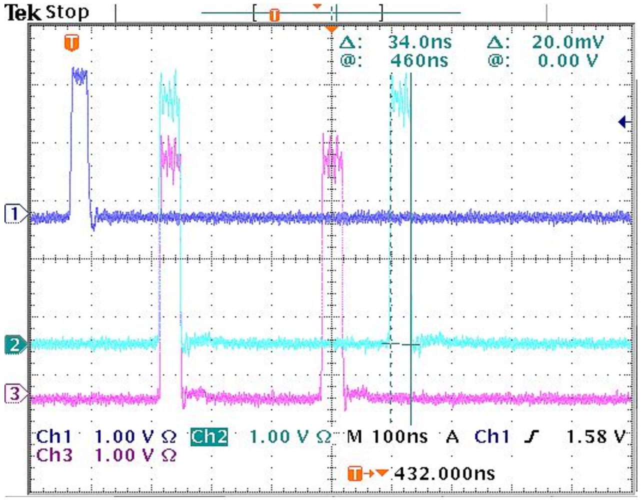
varying coupling
ratios



Characteristics of the 2x4 modes TMD
using bright light and a fast photo diode

3 coupler multimode TMD (2x4 modes)

Classical light input - APD detection



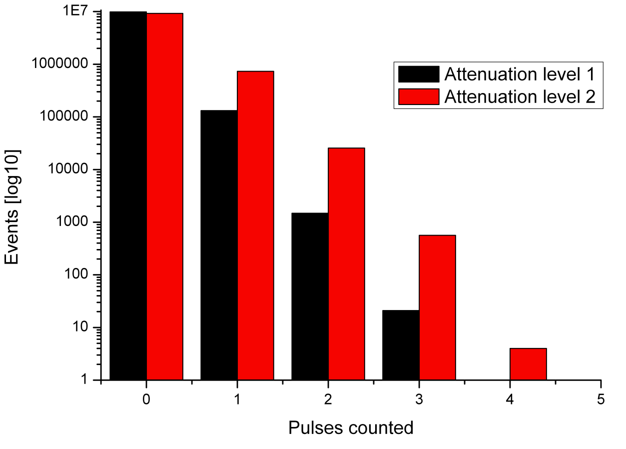
trigger

channel 1 output

channel 2 output

Analysis:
fast electronics
and counting software

Result:
detected statistics
for coherent light



TMD data acquisition

Report on TDC Data

File Name:

`425nWC.LoopyMM.Report.tex`

Input Name:

`425nWC.bin`

various measurement statistics

Total Singles in Channel 0:	[illegible]
Frames with Singles in Channel 0:	1493271
Total Singles in Channel 1:	1701555
Frames with Singles in Channel 1:	1692283
Total Singles in Channel 2:	11837337
Frames with Singles in Channel 2:	11594733
Total Singles in Channel 3:	11644127
Frames with Singles in Channel 3:	11411195
Samples:	26686373
Approx. Trigger Frequency (Hz):	9.9983e+05
Passed Time (s):	300.0000
TDC Bin Width (s):	8.2304e-11
TDC Time Offset (s):	-5.0000e-08
Min dt (s):	1.9588e-08
Max dt (s):	1.0750e-06
Total Gated Singles in Loopy:	14064051
Frames with Gated Singles in Loopy:	13774241
Total UnGated Singles in Loopy:	9417413
Total Gated Singles in Loopy-Trigger:	1763540
Frames with Gated Singles in Loopy-Trigger:	1758471
Total UnGated Singles in Loopy-Trigger:	1441369
Total Gated Singles in Coincidence Gate 1:	14064051
Frames with Gated Singles in Coincidence Gate 1:	13774241
Total UnGated Singles in Coincidence Gate 1:	9417413
Total Gated Singles in Coincidence Gate 2:	1763540
Frames with Gated Singles in Coincidence Gate 2:	1758471
Total UnGated Singles in Coincidence Gate 2:	1441369
Coincidenes in Gate 1 and Gate 2:	280981
Efficiency in Gate 1:	0.1598
Efficiency in Gate 2:	0.0204

Click Statistics

Loopy Bin Statistics	Probability
2120247	0.1508
1750726	0.1245
1460916	0.1039
[illegible]00	0.1261
[illegible]59	0.1196
[illegible]64	0.1073
[illegible]68	0.1131
2176671	0.1548

parameter for convolution matrix

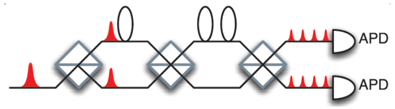
Click Statistics

Conditional (CLoopySM.txt)	Probability
1477490	0.8402
271289	0.1543
9525	0.0054
166	0.0001
1	0.0000
0	0.0000
0	0.0000
0	0.0000
0	0.0000

click statistics conditioned & unconditioned

Click Statistics

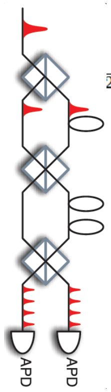
Unconditional (CLoopyMM.txt)	Probability
286173409	0.9541
13487967	0.0450
282760	0.0009
3492	0.0000
22	0.0000
0	0.0000
0	0.0000
0	0.0000
0	0.0000



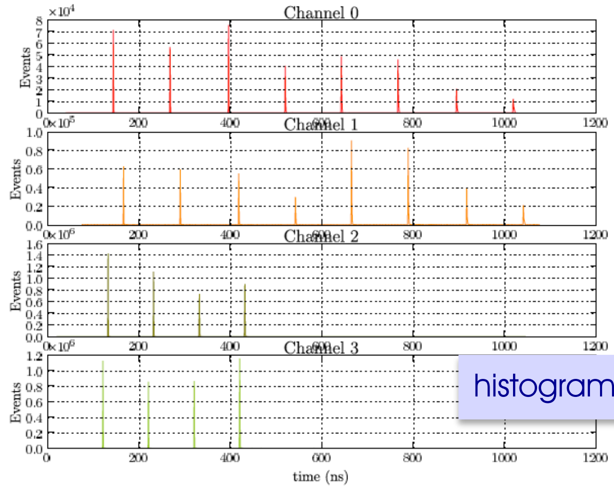
Matrix Statistics

Cond.Loopy (CLoopySM.txt)

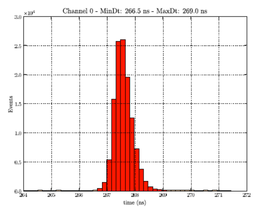
284695919	13216678	273235	3326	21	0	0	0	0
1473677	270166	9407	163	1	0	0	0	0
3807	1118	118	2	0	0	0	0	0
6	5	0	1	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	[illegible]	[illegible]	[illegible]
0	0	0	0	0	0	[illegible]	[illegible]	[illegible]
0	0	0	0	0	0	[illegible]	[illegible]	[illegible]
0	0	0	0	0	0	[illegible]	[illegible]	[illegible]
0	0	0	0	0	0	[illegible]	[illegible]	[illegible]
0	0	0	0	0	0	[illegible]	[illegible]	[illegible]
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0

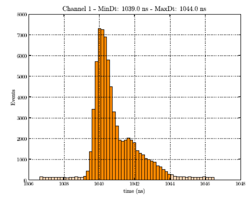


correlation matrix

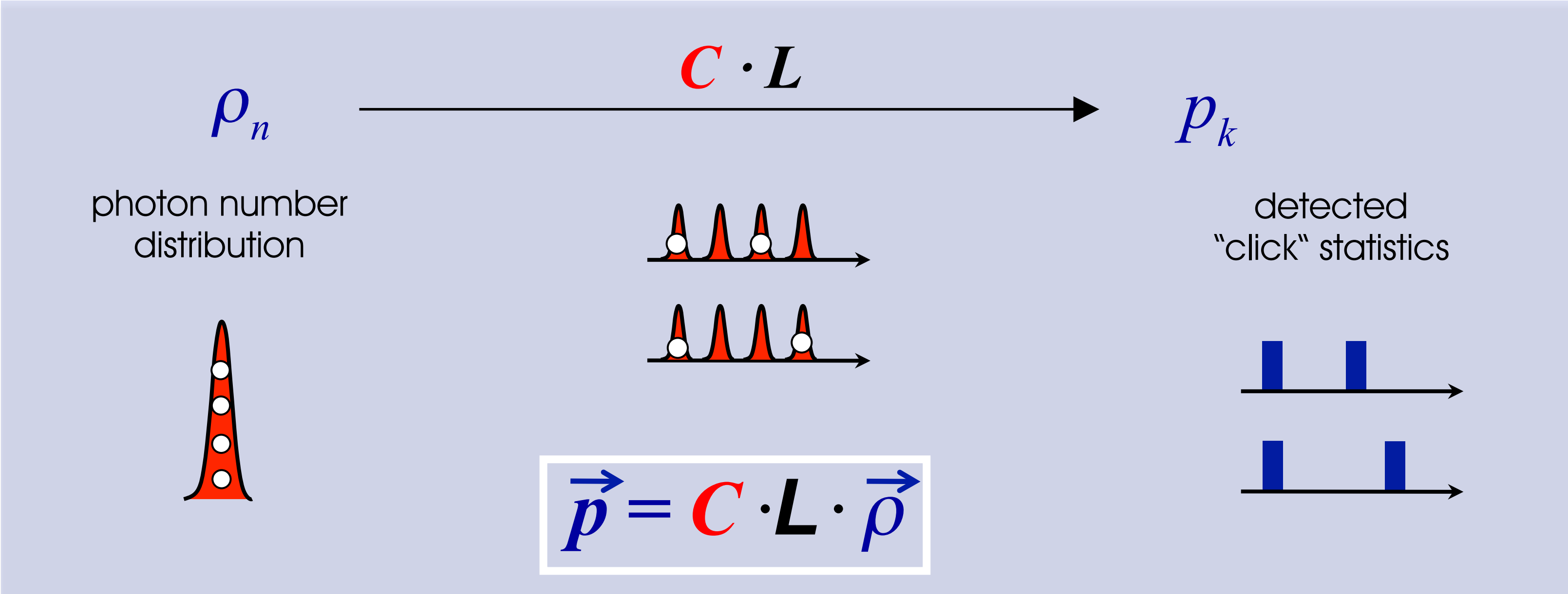


histograms





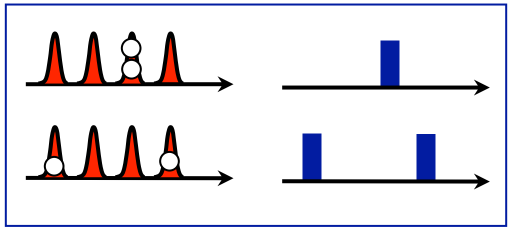
Modelling the TMD



Convolution matrix C :

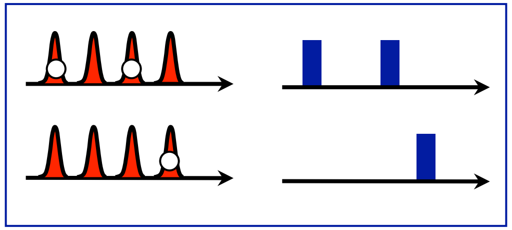
takes into account imperfect splitting of photons

$$p_k = \sum_n p(k \mid n)\, \rho_n\,, \quad \vec{p} = C\,\vec{\rho}$$



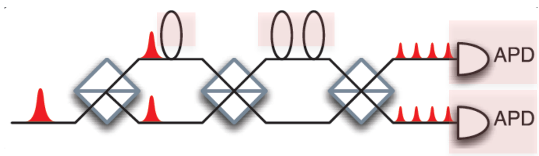
Loss matrix L :

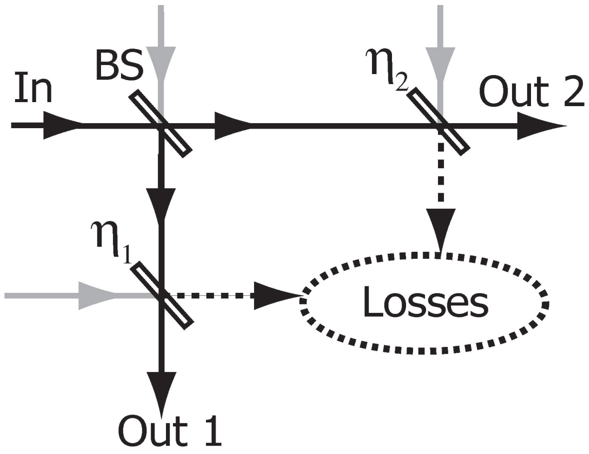
takes into account loss of photons

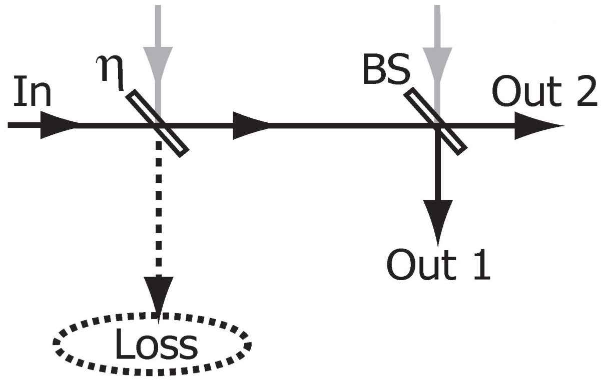


Dealing with losses

For single input mode to TMD: **losses are independent of the convolution**

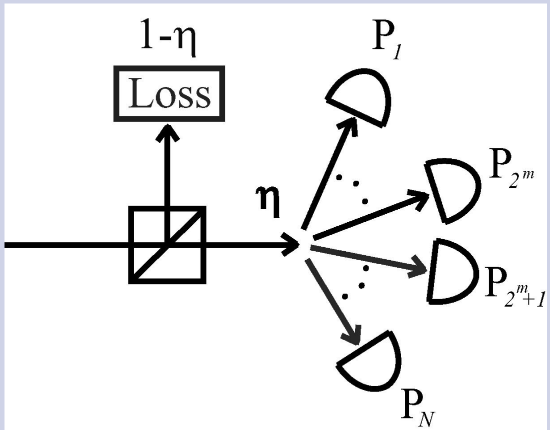






$$\eta = \eta_1(1-\varepsilon) + \varepsilon\eta_2$$

$$\tilde{\varepsilon} = \frac{\varepsilon\eta_2}{\eta}$$



Binomial distribution:

$$p_k = \sum_n \binom{n}{k} \eta^k (1-\eta)^{n-k} \rho_n\,, \quad \vec{p} = L\vec{\rho}$$

Inversion

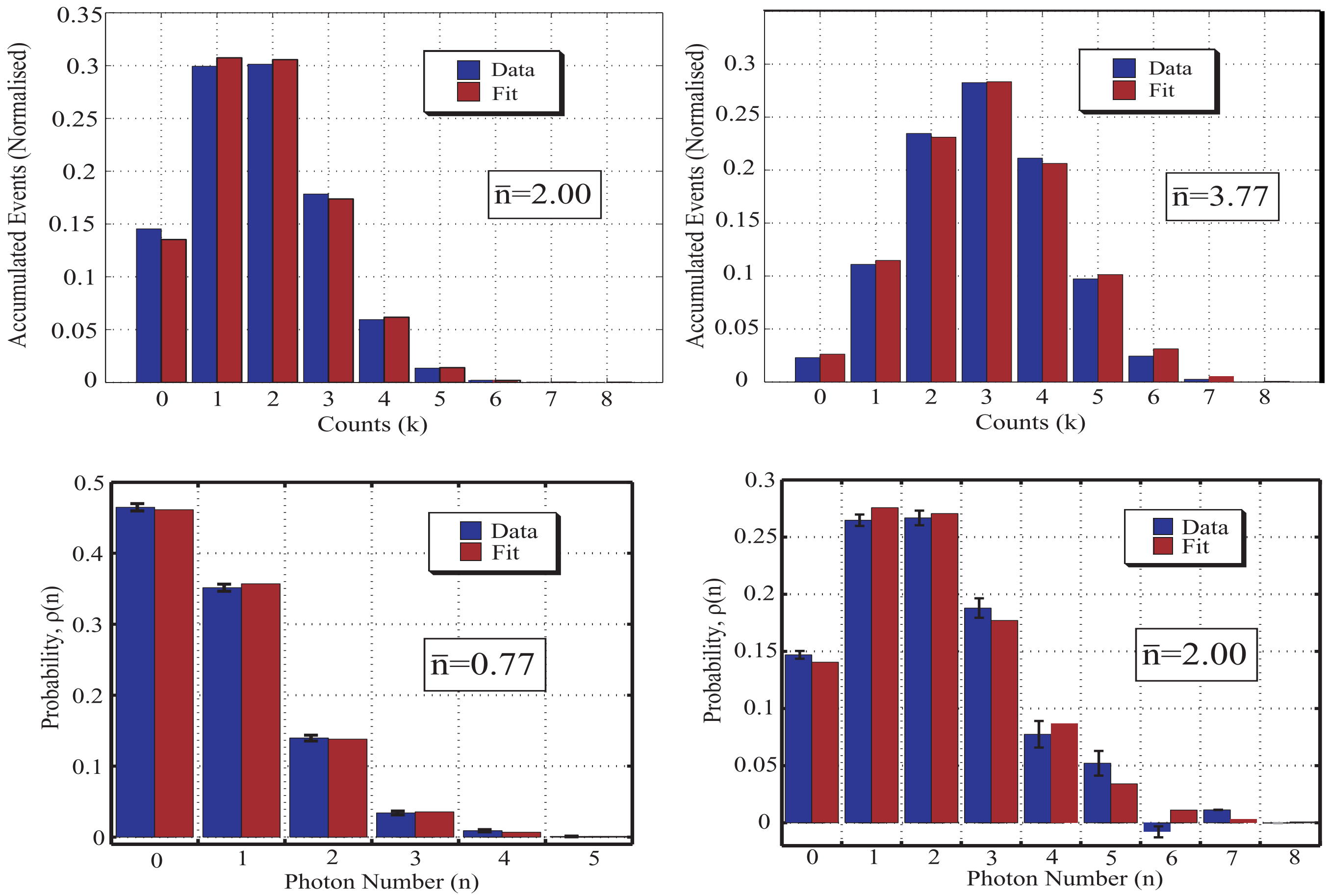
Coherent light statistics

estimation method

$$L C \vec{\rho} - \vec{p}_{est} = 0$$

direct inversion

$$\vec{\rho} = L^{-1} C^{-1} \vec{p}$$



Daryl Achilles, Christine Silberhorn, Cezary Sliwa, Konrad Banaszek, and Ian A. Walmsley, Michael J. Fitch, Bryan C. Jacobs, Todd B. Pittman, James D. Franson, J. Mod. Opt (2004)